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HEAVY ION PHYSICS

The structure of the nucleon

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Abstract. Experimental data on electromagnetic and weak form factors of the nucleon are analyzed in a two-component model with a quark-like intrinsic structure surrounded by a meson cloud. The contribution from strange quarks is discussed and compared with recent data from the G0 Collaboration.

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1. Introduction

Electromagnetic and weak form factors are key ingredients to the understanding of the internal structure of the nucleon, since they contain the information about the distributions of charge and magnetization. Evidence that the nucleon is a composite particle is, among others, provided by the anomalous magnetic moment, the finite size, and the scaling properties observed in deep-inelastic scattering experiments.

The complex structure of the proton manifested itself once again in recent polarization transfer experiments [1] which showed that the ratio of electric and magnetic form factors of the proton exhibits a dramatically different behavior as a function of the momentum transfer as compared to the generally accepted picture of form factor scaling obtained from the Rosenbluth separation method [2].

In recent experiments, parity-violating elastic electron-proton scattering has been used to probe the contribution of strange quarks to the structure of the nucleon. The strange quark content of the form factors can be determined assuming charge symmetry and combining parity-violating asymmetries with measurements of the electric and magnetic form factors of the proton and neutron.

The aim of this contribution is to present a study of the electromagnetic and strange form factors of the nucleon in a two-component model [3, 4]. As an illustration, the results for proton and neutron form factor ratios and strange form

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factors are presented and compared to recent experimental data.

2. Nucleon form factors

The form factors of the nucleon arise from matrix elements of the corresponding current operators

$$\langle N \,| J_\mu |\, N \rangle = \bar{u}_N \left[F_1(Q^2)\, \gamma^\mu + \frac{i}{2M_N} F_2(Q^2)\, \sigma^{\mu\nu} q_\nu \right] u_N \; . \tag{1}$$

Here F_1 and F_2 are the Dirac and Pauli form factors which are functions of the squared momentum transfer $Q^2 = -q^2$. The electric and magnetic form factors, G_E and G_M, are obtained from F_1 and F_2 by the relations $G_E = F_1 - \tau F_2$ and $G_M = F_1 + F_2$ with $\tau = Q^2/4M_N^2$.

Different models of the nucleon correspond to different assumptions about the Dirac and Pauli form factors. In the present model, the external photon couples both to an intrinsic three-quark structure described by the form factor $g(Q^2)$, and to a meson cloud via vector-meson (ρ, ω and ϕ) dominance (VMD). In the original VMD calculation [3], the Dirac form factor was attributed to both the intrinsic structure and the meson cloud, and the Pauli form factor entirely to the meson cloud. In [4], it was shown that the addition of an intrinsic part to the isovector Pauli form factor as suggested by studies of relativistic constituent quark models in the light-front approach [5, 6], improves the results for the neutron elecric and magnetic form factors considerably. These considerations lead to the following form of the isoscalar and isovector form factors [4]

$$\begin{aligned}
F_1^{I=0}(Q^2) &= \frac{1}{2} g(Q^2) \left[1 - \beta_\omega - \beta_\phi + \beta_\omega \frac{m_\omega^2}{m_\omega^2 + Q^2} + \beta_\phi \frac{m_\phi^2}{m_\phi^2 + Q^2} \right] \; , \\
F_2^{I=0}(Q^2) &= \frac{1}{2} g(Q^2) \left[\alpha_\omega \frac{m_\omega^2}{m_\omega^2 + Q^2} + \alpha_\phi \frac{m_\phi^2}{m_\phi^2 + Q^2} \right] \; , \\
F_1^{I=1}(Q^2) &= \frac{1}{2} g(Q^2) \left[1 - \beta_\rho + \beta_\rho \frac{m_\rho^2}{m_\rho^2 + Q^2} \right] \; , \\
F_2^{I=1}(Q^2) &= \frac{1}{2} g(Q^2) \left[\frac{\mu_p - \mu_n - 1 - \alpha_\rho}{1 + \gamma Q^2} + \alpha_\rho \frac{m_\rho^2}{m_\rho^2 + Q^2} \right] \; .
\end{aligned} \tag{2}$$

This parametrization ensures that the three-quark contribution to the anomalous magnetic moment is purely isovector, as given by $SU(6)$. For the intrinsic form factor a dipole form $g(Q^2) = (1 + \gamma Q^2)^{-2}$ is used which is consistent with p-QCD and coincides with the form used in an algebraic treatment of the intrinsic three-quark structure [7].

The large width of the ρ meson is crucial for the small Q^2 behavior of the form factors and is taken is taken into account in the same way as in [3, 4]. For small

values of Q^2 the form factors are dominated by the meson dynamics, whereas for large values the modification from dimensional counting laws from p-QCD can be taken into account by scaling Q^2 with the strong coupling constant [8].

The Dirac and Pauli form factors that correspond to the strange current are factorized in terms of the product of an intrinsic part $g(Q^2)$ and a contribution from the meson cloud as

$$\begin{aligned} F_1^s(Q^2) &= \frac{1}{2}g(Q^2)\left[\beta_\omega^s \frac{m_\omega^2}{m_\omega^2+Q^2} + \beta_\phi^s \frac{m_\phi^2}{m_\phi^2+Q^2}\right] , \\ F_2^s(Q^2) &= \frac{1}{2}g(Q^2)\left[\alpha_\omega^s \frac{m_\omega^2}{m_\omega^2+Q^2} + \alpha_\phi^s \frac{m_\phi^2}{m_\phi^2+Q^2}\right] . \end{aligned} \tag{3}$$

The β's and α's in Eqs. (2) and (3) are not independent of one another. The coefficients appearing in the isoscalar and strange form factors depend on the same nucleon-meson and current-meson couplings [9]. In addition, they are constrained by the electric charges and magnetic moments of the nucleon

$$\begin{aligned} \alpha_\omega &= \mu_p + \mu_n - 1 - \alpha_\phi , \\ \beta_\omega &= -\beta_\phi \tan(\Theta_0+\epsilon)/\tan\epsilon . \end{aligned} \tag{4}$$

The strange couplings can be expressed as

$$\begin{aligned} \beta_\omega^s/\beta_\omega = \alpha_\omega^s/\alpha_\omega &= -\sqrt{6}\,\sin\epsilon/\sin(\Theta_0+\epsilon) , \\ \beta_\phi^s/\beta_\phi = \alpha_\phi^s/\alpha_\phi &= -\sqrt{6}\,\cos\epsilon/\cos(\Theta_0+\epsilon) . \end{aligned} \tag{5}$$

Eqs. (4) and (5) only depend on the mixing angles between the ω and ϕ isoscalar mesons

$$\begin{aligned} |\omega\rangle &= \cos\epsilon\,|\omega_0\rangle - \sin\epsilon\,|\phi_0\rangle , \\ |\phi\rangle &= \sin\epsilon\,|\omega_0\rangle + \cos\epsilon\,|\phi_0\rangle , \end{aligned} \tag{6}$$

where $|\omega_0\rangle = \left(u\bar{u}+d\bar{d}\right)/\sqrt{2}$ and $|\phi_0\rangle = s\bar{s}$ are the ideally mixed states characterized by the mixing angle θ_0 with $\tan\theta_0 = 1/\sqrt{2}$. The mixing angle ϵ has been determined from the decay properties of the ω and ϕ mesons to be $\epsilon = 0.053$ rad [10].

3. Results

In order to calculate the nucleon form factors in the two-component model the five coefficients, γ from the intrinsic form factor, β_ϕ and α_ϕ from the isoscalar couplings, and β_ρ and α_ρ from the isovector couplings, are determined in a least-square fit to the electromagnetic form factors of the proton and the neutron using the same data set as in [4].

In Figs. 1 and 2, the form factors ratios for the proton and neutron are compared with experimental data. The linear drop in the proton form factor ratio was

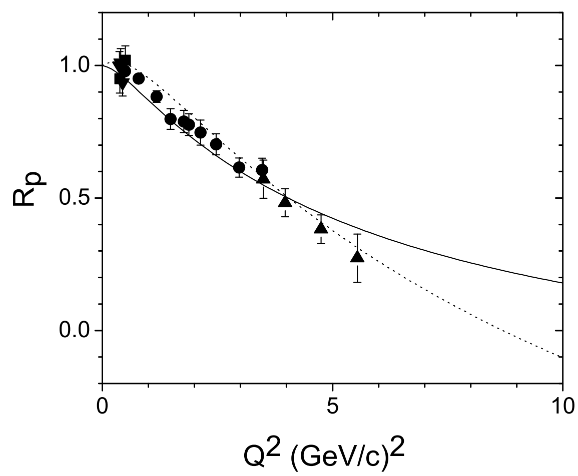

Fig. 1. Comparison between the experimental and theoretical proton form factor ratio $R_p = \mu_p G_{E_p}/G_{M_p}$. The experimental data are taken from a compilation in [4]. The solid line is from the present calculation and the dotted line from [3].

predicted as early as 1973 in a VMD model [3] (dotted line) and later also in a chiral soliton model [11]. The experimental data for the neutron form factor ratio [12] are in agreement with the VMD model of [3] for small values of Q^2, but not so for higher values of Q^2. The present calculation (solid line) is in good agreement with the data, especially for the neutron.

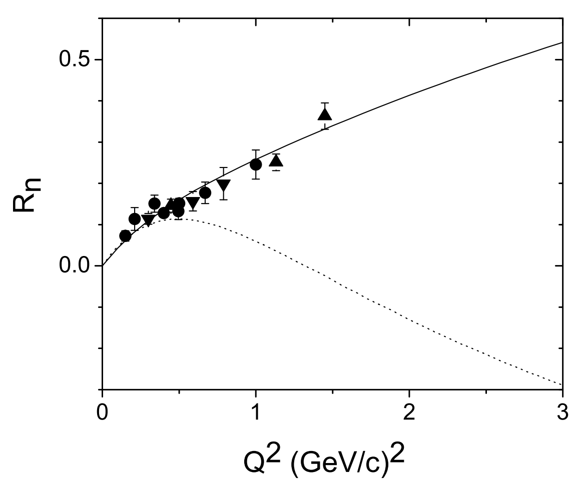

Fig. 2. As Fig. 1, but for the neutron form factor ratio $R_n = \mu_n G_{E_n}/G_{M_n}$.

The strange form factors can now be obtained by combining Eqs. (3) and (5).

As a result, the strange magnetic moment is given by

$$\mu_s = G_M^s(0) = \frac{1}{2}(\alpha_\omega^s + \alpha_\phi^s) = 0.315\,\mu_N \ , \tag{7}$$

a positive value, in contradiction to most theoretical values, but in agreement with recent experimental evidence from the SAMPLE Collaboration which determined the strange magnetic form factor at $Q^2 = 0.1$ (GeV/c)^2 to be $G_M^s = 0.37 \pm 0.20 \pm 0.26 \pm 0.07$ [13]. An analysis of the world data gives $G_M^s(0.1) = 0.55 \pm 0.28$ [14].

Fig. 3 shows that the calculated values for the strange form factor combination $G_E^s + \eta G_M^s$ are in good agreement with the experimental ones obtained recently by the G0 Collaboration [15].

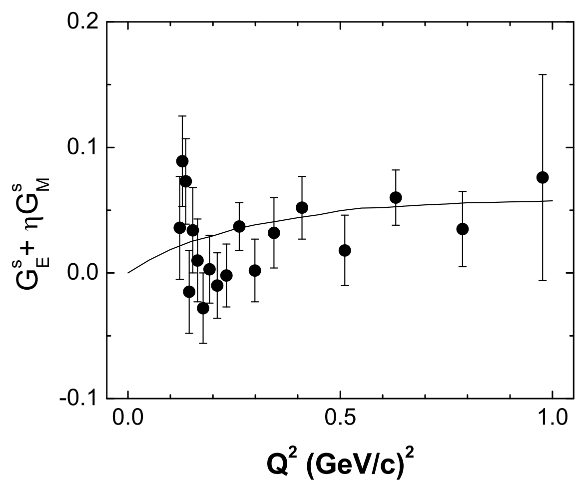

Fig. 3. Comparison between theoretical and experimental values of the strange form factor $G_E^s + \eta G_M^s$. The experimental values are taken from the G0 Collaboration [15].

4. Summary and conclusions

In this contribution, the recent data on electromagnetic and weak form factors of the nucleon were analyzed in a two-component model which consists of an intrinsic (three-quark) structure and a meson cloud whose effects were taken into account via VMD couplings. The parameters in the model are completely determined by the electromagnetic form factors of the proton and neutron. The strange couplings follow directly from the electromagnetic ones and do not involve any new parameters. On the contrary, the fact that the net contribution of the strange quarks to the electric charge of the nucleon is zero, leads to an extra constraint relating β_ω and β_ϕ.

A good overall agreement is found both for the form factor ratios of the proton and neutron and the strange form factor as measured by the G0 Collaboration. The size of the intrinsic structure is found to be ~ 0.49 fm. The strange magnetic moment is calculated to be positive in agreement with recent data from parity violation electron scattering.

The first results from the SAMPLE [13], HAPPEX [14, 16, 17], G0 [15] and PVA4 [18] collaborations have shown evidence for a nonvanishing strange quark contribution to the charge and magnetization distributions of the nucleon. Future experiments hold great promise to be able to unravel the contributions of the different quark flavors to the electromagnetic and axial form factors, and thus to give new insight into the complex internal structure of the nucleon.

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